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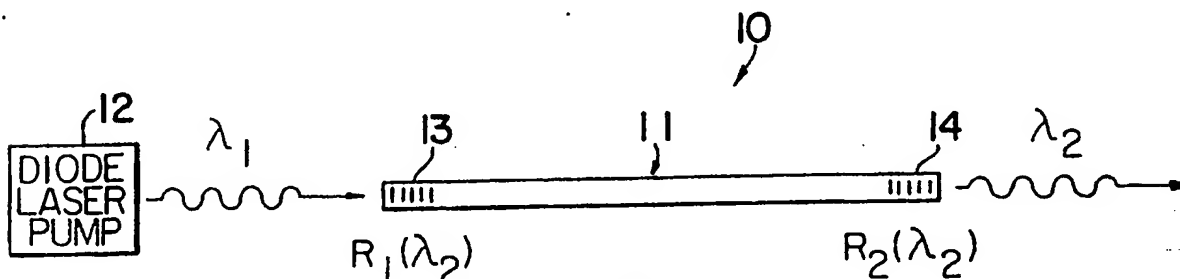
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(54) Embedded Bragg grating pumped lasers.

(57) An optical fiber laser arrangement includes an optical fiber section that has a solid waveguiding portion capable of guiding light along a longitudinal axis between longitudinally spaced ends thereof. The waveguiding portion is at least in part of a material that emits light in response to stimulation by light. A pumping laser is used to launch stimulating light into the waveguiding portion for longitudinal propagation therein. The waveguiding portion has at least one Bragg grating permanently embedded therein. The

Bragg grating redirects light initially propagating in one direction into a different direction, and consists of a multitude of longitudinally consecutive grating elements constituted by periodic refractive index perturbations with a given periodicity that cumulatively cause light of a predetermined wavelength depending on the periodicity to change its direction of propagation from one of the directions to the other and to constructively interfere when propagating in the other direction.

**FIG. 1**

EMBEDDED BRAGG GRATING PUMPED LASERS

Technical Field

The present invention relates to pumped optical fiber lasers in general, and more particularly to lasers of the above type which utilize reflective elements in the form of gratings.

Background Art

There are already known various constructions of pumped optical fiber lasers, among them such utilizing fully or partially reflective coatings on the respective end faces of the optical fiber sections constituting the laser resonance cavities, and such using external mirrors to delimit the laser cavities. Even though these solutions have achieved some degree of success and/or acceptance in the laser manufacturing and utilization fields, they still suffer of certain drawbacks. So, for instance, because of the physical properties of the heretofore used reflecting elements, and the temperature related changes in their configurations, it is very difficult if not impossible to assure under all operating conditions that the light emitted by such known lasers will have the desired wavelength and that the wavelength band at which the lasers of this type issue light will be in the desired narrow range around a central wavelength.

Accordingly, it is a general object of the present invention to avoid the disadvantages of the prior art.

More particularly, it is an object of the present invention to provide pumped optical fiber laser arrangements which do not possess the disadvantages of the known arrangements of this kind.

Still another object of the present invention is so to develop the arrangements of the type here under consideration as to improve their performance in terms of wavelength stability and emission range narrowness.

It is yet another object of the present invention to devise arrangements of the above type which are able to achieve high conversion efficiencies.

A concomitant object of the present invention is to design the optical fiber lasers of the above type in such a manner as to be relatively simple in construction, inexpensive to manufacture, easy to use, and yet reliable in operation.

Disclosure of the Invention

In keeping with these objects and others which will become apparent hereafter, one feature of the present invention resides in an optical fiber laser arrangement which comprises an optical fiber sec-

tion including a solid waveguiding portion capable of guiding light along a longitudinal axis between longitudinally spaced ends thereof. The waveguiding portion is at least in part of a material that emits light in response to stimulation by light. The arrangement further includes means for launching stimulating light into the waveguiding portion for longitudinal propagation therein, and means in the waveguiding portion for redirecting light initially propagating in a predetermined direction into a different direction. According to the present invention, such redirecting means includes a Bragg grating permanently embedded in the waveguiding portion and consisting of a multitude of longitudinally consecutive grating elements constituted by periodic refractive index perturbations with a given periodicity that cumulatively cause light of a predetermined wavelength depending on the periodicity to change its direction of propagation from one of the directions to the other and to constructively interfere when propagating in the other direction.

Brief Description of the Drawing

The present invention will be described in more detail below with reference to the accompanying drawing in which:

Figure 1 is a somewhat simplified side elevational view of an optically pumped optical fiber laser arrangement of the present invention; Figure 2 is a view similar to that of Figure 1 but showing a modification of the arrangement thereof;

Figure 3 is a simplified perspective view of an arrangement for applying longitudinal stresses to an optical fiber, which is suited for use in the laser arrangement of the type revealed in Figure 2;

Figure 4 is another view similar to that of Figure 1 but showing a further modification of the arrangement thereof;

Figure 5 is a further view similar to that of Figure 1 but showing an additional modification of the arrangement thereof;

Figure 6 is a somewhat simplified perspective view of a multicavity optically pumped optical fiber laser arrangement utilizing the concepts depicted in Figure 1;

Figure 7 is also a view similar to that of Figure 1 but showing the utilization of the concepts of Figure 4 in conjunction with two optical fibers; and

Figure 8 is a view similar to that of Figure 3 but showing a multiple Bragg grating optically pumped optical fiber laser arrangement.

Best Mode for Carrying Out the Invention

Referring now to the drawing in detail, it is to be mentioned first that the same reference numerals, possibly supplemented with reference characters and/or numerals where appropriate, have been used throughout to identify corresponding parts. It may be seen in Figure 1 that the reference numeral 10 identifies a pumped optical fiber laser arrangement 10 in its entirety. The arrangement 10 includes, as its main components, an optical fiber section 11 and a laser pump 12 which is of any known construction and advantageously is constituted by or includes a diode laser. The laser pump 12 issues light of a wavelength λ_1 , and this light is launched, in any well known manner, into the optical fiber section 11 for propagation longitudinally thereof. As is well known to those practicing in this field, the optical fiber section 11 may include a fiber core and a cladding surrounding the core, in which case the light from the laser pump 12 is launched into the core and is guided therein.

The optical fiber section 11 (preferably the core thereof) is shown to be provided with two gratings 13 and 14 which are spaced from one another in the longitudinal direction of the section 11 and are shown to be situated at the respective ends of the section 11. The gratings 13 and 14 are reflective, to a greater or lesser degree, but only to light at a wavelength λ_2 (actually, in a very narrow band around this central wavelength), being substantially transparent to light at all other wavelengths, including, at least as far as the grating 13 is concerned, the pumping wavelength λ_1 . Thus, the gratings 13 and 14 act as reflectors and thus axially delimit the laser cavity in which the lasing at the wavelength λ_2 takes place.

It is currently preferred for the gratings 13 and 14 to be of the type, and to be made in accordance with the method, disclosed in the commonly owned U. S. Patent No. 4,807,805 the disclosure of which is incorporated herein by reference to the extent necessary to provide additional explanation of the type of the Bragg gratings that is particularly suited for use in the optical fiber laser arrangement 10. As more fully explained in the above patent, gratings of this type act as wavelength selective reflectors. An embedded grating of specified periodicity will partially or wholly reflect a specific wavelength of an optical signal carried by the fiber section 11. This type of grating, which has been developed for sensing stress and/or temperature changes in structures, is incorporated or embedded in the core of an optical fiber by a method disclosed in the above patent. As discussed there, permanent periodic gratings of this kind can be provided or impressed in the core of an optical fiber by exposing the core through the cladding to

the interference pattern of two compatible ultraviolet light beams that are directed against the optical fiber at two angles relative to the fiber axis that complement each other to 180° . This results in a situation where the material of the fiber core has permanent periodic variations in its refractive index impressed therein by the action of the interfering ultraviolet light beams thereon, with the individual grating elements (i.e. the periodically repetitive regions of the core exhibiting the same refractive index behavior) being oriented normal to the fiber axis so as to constitute a Bragg grating. The embedded Bragg grating of this kind reflects, of the light launched into or otherwise guidedly propagating in the fiber core in a propagation direction that brings it to the respective grating 13 or 14, only that having a wavelength within a very narrow range around a central wavelength λ_2 that is dependent on the grating element periodicity, back along the fiber axis opposite to the original propagation direction while being substantially transparent to light at wavelengths outside the aforementioned narrow band so that it does not adversely affect the passage of such other light therethrough. In effect, this type of grating creates a narrow notch in the transmission spectrum and, by the same token, a similarly narrow peak in the reflection spectrum. This reflection spectrum peak is being utilized in accordance with the present invention to determine the lasing wavelength λ_2 , and the axial length of each of the gratings 13 and 14 is selected in such a manner as to obtain the desired reflectivities $R_1(\lambda_2)$ and $R_2(\lambda_2)$ at the gratings 13 and 14, respectively.

For the optical fiber section 11 to operate as an optically pumped laser, the material of at least the core thereof is rare-earth doped. On the other hand, the above patent teaches the making of the gratings of the type here under consideration in germanium doped optical fiber cores. In accordance with the present invention, it is contemplated either to impress the gratings 13 and 14 directly into the (rare-earth doped) active material of the optical fiber section (or its core), or to form such gratings 13 and 14 in optical fiber pieces (or cores thereof) of passive materials, and to splice the same with an optical fiber piece made of, or having a core of, the active material, to thus obtain the optical fiber section 11. In either event, the optical fiber section 11 is unitary or integral, so that no problems arising from the presence of interfaces or gaps are encountered. This comment is equally applicable to the optical fiber embedded grating pumped laser arrangement constructions that will be described below.

Turning now to Figure 2 of the drawing, it may be seen therein that in this instance the optical fiber laser arrangement 10a includes a grating 13a

which is tunable as far as its central wavelength λ_2 is concerned. The laser cavity is shown to be delimited by conventional reflectors 15 and 16 (such as reflective coatings on the respective fiber end faces) of respective reflectivities R_1 and R_2 in the wavelength range over which the central wavelength λ_2 is tunable, while at least the reflector or mirror 15 is highly transparent to light at the wavelength λ_1 . The tuning of the variable grating 13a can be accomplished, for instance, by winding the portion of the section 11 that includes the variable grating 13a around a mandrel, and by changing the diameter or circumferential dimension of such mandrel, for instance by the application of an electrical potential difference to the mandrel when the latter is made of a piezoelectric material. It will be appreciated that, by thus introducing longitudinal strains and stresses into the grating region 13a, the periodicity of the grating 13a, that is the distance between longitudinally adjacent grating elements that exhibit the same refractive index variation behavior (and possibly also the overall or average index of refraction of the grating material) changes, with attendant change in the central wavelength λ_2 .

In the alternative, the gratings 13 and 14 of Figure 1, or the reflectors 15 and 16 of Figure 2, can be of the variable variety as well. In this case, as illustrated in Figure 3 of the drawing, the portion of the optical fiber section 11b that includes the variable gratings 13b and 14b (or the variable grating 13a and the variable grating reflectors 15 and 16) may be wrapped around a mandrel 17 that again may be of piezoelectric material and is then radially expanded, as indicated by arrows, by applying electrical potential differences thereto, so as to change the circumference thereof and thus ultimately the spacings between the respective grating elements with attendant shifts in the central wavelength λ_2 .

The arrangement 10c depicted in Figure 4 of the drawing is similar to that shown in Figure 1 except that the grating 14c redirects the light of the wavelength λ_2 out of the fiber section 11c at an angle (as shown, a substantially a right angle) to the longitudinal axis of the section 11c. This grating 14c can be formed, for instance, by using the method disclosed in the copending commonly owned U. S. patent application Serial No. 7/456,450, as much of the disclosure of which as may be needed to supplement that provided here with respect to this aspect of the present invention is incorporated herein by reference. In any event, the grating 14c constitutes not only a reflector that delimits, at its end, the laser cavity, but also a tap for light of the wavelength λ_2 .

Figure 5 shows the application of the principles involved in the arrangement 10 of Figure 1 to a

multiple wavelength embedded grating laser arrangement 10d. In this case, the laser source 14 launches light into a shared input optical fiber portion 11a which is then coupled to a plurality of individual laser optical fiber sections 11d₁ to 11d_n - (wherein n is any selected integral number), which are shown to be but need not be spatially parallel and each of which contains a laser cavity delimited by respective gratings 13d₁ to 13d_n on the one hand, and 14d₁ to 14d_n on the other hand. Herein, the associated ones of the gratings 13d₁ to 13d_n and 14d₁ to 14d_n (i.e. those located in the respective ones of the sections 11d₁ to 11d_n) are both reflective to light having the same central wavelength λ_1 to λ_n but the wavelengths λ_1 to λ_n are all different.

Figure 6 of the drawing is an illustration of a multicavity embedded grating optical fiber laser arrangement 10e containing, in this example, five optical fiber sections 11e₁ to 11e₅ (e.g. clad optical fibers or unclad optical fiber cores) that are contained in a common envelope 18 (such as in a common outer cladding). The laser cavities of the optical fiber sections 11e₁ to 11e₅ are delimited by respective gratings 13e₁ to 13e₅ and 14e₁ to 14e₅, and the pumping laser source 14 launches light, in any known manner, into all of the optical fiber sections 11e₁ to 11e₅. As shown, all of the gratings 13e₁ to 13e₅ and 14e₁ to 14e₅ are reflective to light at the same wavelength λ_2 , so that the light issued from such parallel laser cavities constructively combines, giving the arrangement 10e an optical output power that is a multiple of that of the arrangement 10 of Figure 1.

As shown in Figure 7, the arrangement 10f depicted therein includes two parallel fiber sections 11f₁ and 11f₂. The fiber section 11f₁ includes gratings 13f₁ and 14f₁ which are akin to and operate in a manner similar to that of the grating 14c of Figure 4 and which are reflective to light at the wavelength λ_1 issued by the pumping laser source 14. On the other hand, the fiber section 11f₂ includes, in addition to gratings 13f₂ and 14f₂ that also are akin to and operate in a manner similar to that of the grating 14c and reflect light at the wavelength λ_1 , additional gratings 13f₃ and 14f₃ which are reflective to light at a wavelength λ_2 . Thus, optical power is transmitted between the sections 11f₁ and 11f₂ at the central wavelength λ_1 due to the cooperation of the gratings 13f₁ and 14f₁ with the gratings 13f₂ and 14f₂, whereas the fiber section 11f₂ issues laser light at the central wavelength λ_2 .

Last but not least, Figure 8 of the drawing is an illustration of an arrangement 10g of the type described above in which, however, the optical power is increased by launching light into the optical fiber section 11g at a plurality of locations. In the illus-

trated example of construction of the arrangement 10g, the pumping light source is constituted by a pumping laser array 14g, and the optical fiber section is wound around a cylindrical support 17g in such a manner that a plurality of embedded gratings 14g₁ to 14g_m (m being an arbitrarily chosen integral number) of the type described above in conjunction with the grating 14c of Figure 4 is exposed to laser light issued by the pumping laser array 14g.

While the present invention has been illustrated and described as embodied in several particular constructions of an embedded grating laser arrangement, it will be appreciated that the present invention is not limited to this particular example; rather, the scope of protection of the present invention is to be determined solely from the attached claims.

Claims

1. An optical fiber laser arrangement comprising an optical fiber section including an elongated solid waveguiding portion capable of guiding light along a longitudinal axis between longitudinally spaced ends thereof, at least one longitudinal region of said waveguiding portion being of a rare-earth-doped material capable of emitting stimulated light in response to stimulation by stimulating light;
means for launching stimulating light into said waveguiding portion for longitudinal propagation therein and for stimulating said rare-earth-doped material to emit said stimulated light; and
means in said waveguiding portion for redirecting light initially propagating in a predetermined direction into a different direction, including a Bragg grating permanently embedded in said waveguiding portion and consisting of a multitude of longitudinally consecutive grating elements constituted by periodic refractive index perturbations with a given periodicity that extend all the way across said longitudinal region and cumulatively cause only that of said stimulated light that has a predetermined wavelength depending on said periodicity to change its direction of propagation from one of said directions to the other and to constructively interfere when propagating in said other direction.
2. The arrangement as defined in claim 1, wherein said grating is situated at one of said ends of said waveguiding portion and said grating elements thereof extend substantially normal to said longitudinal axis for said grating to serve as a partially transparent reflector

axially delimiting a laser cavity at said one end of said waveguiding portion.

3. The arrangement as defined in claim 2, and further comprising an additional reflector arranged at the other of said ends of said waveguiding portion and constituted by a grating substantially identical to said Bragg grating and axially delimiting said laser cavity at said other end.
4. The arrangement as defined in any one of claims 1 to 3, further comprising two reflectors each situated at a different one of said ends of said waveguiding portion and axially delimiting a laser cavity thereat; and wherein said grating is situated between said reflectors and all of said grating elements thereof extend at the same oblique angle with respect to said longitudinal axis for a first of said directions to extend longitudinally of said waveguiding portion and a second of said directions to extend out of said waveguiding portion at the location of said grating at a predetermined angle relative to said longitudinal axis.
5. The arrangement as defined in claim 4, wherein at least one of said reflectors is constituted by an additional grating similar to said Bragg grating but with said grating elements thereof extending substantially normal to said longitudinal axis for said grating elements cumulatively to reverse the direction of propagation of the light affected thereby.
6. The arrangement as defined in any one of claims 1 to 5, further comprising an additional optical fiber section similar to and extending substantially parallel to said optical fiber section; and wherein said grating of said additional optical fiber section is situated to receive the light redirected by said grating of said optical fiber section and to redirect the same into said waveguiding portion of said additional optical fiber section for longitudinal propagation therein.

